Faraday Rotation Correction for Passive Microwave Remote Sensing from Space

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Abstract. *Faraday rotation (FR) is one of the main error sources for passive microwave remote sensing from space especially in frequencies less than or equal to 10.7 GHz. In this paper, Faraday rotation correction for the vertical brightness temperature at L band and the third Stokes parameter brightness temperature at 10.7 GHz are discussed. Two approaches are studied to remove the influence of FR: correction by auxiliary data and correction by polarimetric mode. At 1.4 GHz, correction by polarimetric mode performs better than correction by auxiliary data. At 10.7 GHz, correction by auxiliary data is feasible while polarimetric mode correction becomes invalid. We propose a new method of using TEC data released by international GNSS service (IGS) for correction. It has been proved that the residual correction errors are reduced. IGS data method greatly improves the correction accuracy.*

Keywords

Faraday rotation, Stokes parameter, polarimetric mode correction, correction by auxiliary data, international GNSS service (IGS).

1. Introduction

Passive microwave remote sensing has become one of the most important ways for earth observations [1], [2]. At L-band frequency, Soil Moisture and Ocean Salinity (SMOS) mission can provide accurate estimates of soil moisture (SM) and sea surface salinity (SSS) globally [3], [4]. Aquarius mission also provides global observation of SSS [5]. At higher frequencies (above 6.8 GHz), polarimetric microwave radiometer like WindSat can give the information about sea surface wind vector, ice cover, rain rate, and other environmental products [6].

Spaceborne measurement of microwave emission is subject to the influence of ionospheric Faraday rotation (FR) [7, 8]. The second Stokes parameter Q and the third Stokes parameter U are changed when the microwave propagates through the ionosphere. The lower the frequency is, the greater the influence of FR brings. The radiometric errors in the linearly polarized brightness temperatures can be larger than 10K for incidence angles in the range of 30° to 50° at L-band, while the errors of the third stokes parameter U can be greater than 0.5 K at 10.7 GHz. These errors of brightness temperatures will introduce significant deviation in the retrieval of SSS, SM, sea surface wind direction (SSWD) and other environmental parameters.

There are two main approaches for the correction of errors caused by Faraday rotation. One is to calculate FR in definition by using auxiliary data of ionospheric electron density and geomagnetic field [9], [10]. We call it correction by auxiliary data. The other is to correct the errors assuming that the cross polarization brightness temperatures of the earth are zero by using the polarimetric mode of the radiometer [11], [12]. We name it correction by polarimetric mode. For correction of Q, the typical frequency is mainly at L-band while the typical frequency is mainly at 10.7 GHz for correction of U. In this study, the relationship between Stokes parameters and Faraday rotation is discussed. For correction of Q, corrections by different approaches are compared at L-band while for correction of U, a new method is proposed to improve the correction accuracy at 10.7 GHz.

2. Stokes Parameter and Faraday Rotation

The electromagnetic waves emitted from natural media are generally partially polarized. To fully characterize the polarization state of polarized thermal radiation, four parameters I, Q, U and V were introduced by Sir George Stokes [13]. These four parameters are defined as follows:

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \frac{1}{\eta} \begin{pmatrix} \left\langle |E_v|^2 \right\rangle + \left\langle |E_h|^2 \right\rangle \\ \left\langle |E_v|^2 \right\rangle - \left\langle |E_h|^2 \right\rangle \\ 2\,\mathrm{Re}\left\langle E_v E_h^* \right\rangle \\ 2\,\mathrm{Im}\left\langle E_v E_h^* \right\rangle \end{pmatrix} \propto \begin{pmatrix} T_v + T_h \\ T_v - T_h \\ T_3 \\ T_4 \end{pmatrix}. \quad (1)$$

Here, η is the electromagnetic wave impedance, $E_p = \vec{E} \cdot \hat{p}$ ($p = v, h$) is the component of the electric field in polarization direction $\hat{p}$ and T_q ($q = v, h, 3, 4$) is the corresponding brightness temperature. The first Stokes parameter I represents the total radiated power density and the second Stokes parameter Q is the difference of the power density in the vertical and horizontal polarization channels. The third and fourth Stokes parameters brightness temperatures U and V characterize the correlation between the two linear polarizations.

For convenience, a proportional constant is ignored which relates the power density to the brightness temperatures. Hence, the express brightness temperatures are expressed as:

$$T_B = \begin{pmatrix} T_v \\ T_h \\ T_3 \\ T_4 \end{pmatrix} = \begin{pmatrix} (I+Q)/2 \\ (I-Q)/2 \\ U \\ V \end{pmatrix} \quad (2)$$

In the microwave range, the polarization vector of an electromagnetic wave of frequency f undergoes Faraday rotation by an angle φ as the microwave radiation from the earth propagates through the ionosphere. The angle is associated with the ionospheric electron density n_e, the geomagnetic field vector $\vec{B}$ and the propagation direction of the earth radiation $d\vec{s}$ [14]:

$$\varphi = \frac{135}{f^2}\int n_e \vec{B}\cdot d\vec{s} \,. \quad (3)$$

The units in (3) are: $[\varphi]$ = degree, $[f]$ = Hz, $[B]$ = Gauss, $[n_e]$ = m^{-3} and $[ds]$ = m. When looking into the propagation direction of the electromagnetic wave, the electric field polarization vector rotates clockwise if $\varphi > 0$. In order to simplify the computation, we use the thin layer approximation method [15], which assumes that all electrons are concentrated at the ionosphere layer at an altitude h_I above mean sea level:

$$\varphi \approx \frac{1.35}{f^2} VTEC\cdot B_I \cos(\theta)\sec(\phi) . \quad (4)$$

At the incident point of the thin layer represented by the subscript I, VTEC is the vertical total electron content; B_I is the magnetic field intensity; θ is the angle between the magnetic field and wave propagation direction; Φ is the angle between the wave propagation direction and the normal of the surface. We express the VTEC in units of TECU [10^{16} m^{-2}] and the frequency in GHz. According to previous studies, this method has the accuracy about 5% when the incident angle is less than 60° [15], [16]. In this paper, we use this method in the computation of FR with the thin layer altitude h_I = 400 km.

Then we define the vertically and horizontally polarized components of the electric fields received by the satellite by E_{va} and E_{ha}. The subscript a indicates the antenna measurements of microwave radiometer. Therefore, the rotation of the electric field is:

$$\begin{pmatrix} E_{va} \\ E_{ha} \end{pmatrix} = \begin{pmatrix} \cos(\varphi) & -\sin(\varphi) \\ \sin(\varphi) & \cos(\varphi) \end{pmatrix}\cdot\begin{pmatrix} E_v \\ E_h \end{pmatrix} . \quad (5)$$

The rotation of the Stokes parameters can be expressed as:

$$\begin{pmatrix} I_a \\ Q_a \\ U_a \\ V_a \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\varphi) & -\sin(2\varphi) & 0 \\ 0 & \sin(2\varphi) & \cos(2\varphi) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}\cdot\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \quad (6)$$

So the relation between the earth brightness temperatures and the antenna temperatures is:

$$\begin{aligned} T_{va} &= T_v - \Delta T \\ T_{ha} &= T_h + \Delta T \\ Q_a &= Q - \Delta Q \\ U_a &= U - \Delta U \end{aligned} \quad (7)$$

ΔT, ΔQ and ΔU are the brightness temperature errors to be corrected caused by FR:

$$\begin{aligned} \Delta T &= Q\sin^2(\varphi) + \frac{U}{2}\sin(2\varphi) \\ \Delta Q &= 2Q\sin^2(\varphi) + U\sin(2\varphi) \\ \Delta U &= -Q\sin(2\varphi) + 2U\sin^2(\varphi) \end{aligned} \quad (8)$$

If the estimate of FR has an error of $\delta\varphi = \varphi_{real} - \varphi_{estimate}$, the correction residual errors in the brightness temperatures can be considered as the errors caused by a FR angle φ which equals to $\delta\varphi$. Here, the subscript *real* and *estimate* indicate the real and estimated FR respectively. Residual errors of brightness temperatures are differences between the corrected brightness temperatures and the real brightness temperatures without the influence of FR. They are expressed as real brightness temperatures minus estimated brightness temperatures.

It is clear that orthogonal polarization brightness temperature error ΔT is half of ΔQ. Thus, correction for T_v and T_h is equivalent to correction for Q. Because orthogonal polarization brightness temperatures (T_v, T_h) are usually used in geophysical parameter retrieval, we only discuss correction for T_v in our study.

Frequencies (GHz)	FR angle (deg)	ΔT (K)	ΔU (K)
1.4	-11.30	2.65	26.92
6.8	-0.48	3.20×10^{-3}	1.17
10.7	-0.19	1.07×10^{-4}	0.46
18.7	-0.06	-1.33×10^{-4}	0.15
23.8	-0.04	-1.06×10^{-4}	0.10
37	-0.02	-6.13×10^{-5}	0.05

Tab. 1. Faraday rotation angle and corresponding brightness temperature errors at different frequencies. FR is calculated by International Reference Ionosphere (IRI) model at (19.4° N, 109° E) with medium solar activity Sun spot number (SSN) is 50.9. Q is 70 K and U equals to 0.2 K versus 50° incidence angle and 0° scan angle.

Tab. 1 shows the variation of ΔT and ΔU at different FR angles of different frequencies. The Faraday rotation is in inverse proportion to f^2 and decreases rapidly when the frequency grows. For practical application, observations of SSS and SM are mainly at L-band. The retrieval only uses the orthogonal polarization brightness temperatures according to SMOS and Aquarius mission [17], [18]. For the observation of sea surface wind vector, all four Stokes brightness temperatures (T_v, T_h, T_3, T_4) are used for retrieval at higher frequencies (10.7 GHz, 23.8 GHz, 37 GHz) according to WindSat [19]. Moreover, in orthogonal polarization channels at frequencies above 6.8 GHz, the errors caused by FR even can be ignored because they are quite small relative to the calibration accuracy (usually 1 K). However, at 10.7 GHz, the error of U cannot be ignored because the magnitude of U is also small (usually less than 1.5 K). So in this paper, we mainly concentrate on the correction for T_v at 1.4 GHz and for U at 10.7 GHz.

3. Accuracy Requirements

According to (8), the brightness temperature errors caused by Faraday rotation and the correction residual errors are determined by Q, U and φ. Q is closely related to the earth incidence angle. SMOS observations have incidence angles ranging from 0° to 55° with Q value between 0 K and 80 K. Aquarius has three incidence angles for the observation, while the central boresight is 38°. The typical value of Q is 35 K. For WindSat 10.7 GHz fully polarimetric channel, the incidence angle is 49.9° and corresponding typical value of Q is 75 K. Compared with Q, the third Stokes parameter U is usually smaller in two to three orders of magnitude (typically less than 1.5 K) for all channels at different frequencies.

For correction of T_v at 1.4 GHz, Fig. 1 shows the influence of Faraday rotation on the orthogonal polarization channel brightness temperature T_v. Because the magnitude of U is small, the latter term in (8) has little influence on ΔT. So in the computation, we don't consider the variation of U and its value is set to 0.2 K. In real condition, the Faraday rotation angle can reach 20° sometimes, Fig. 1 illustrates that ΔT can go above 10 K at high Q (high incidence angle). This error is large enough to be corrected for both SSS and SM observation. When FR angle decreases, ΔT decreases quickly. So for FR correction, if the misestimate of FR is less than 5°, we can expect a low residual error of less than 1 K.

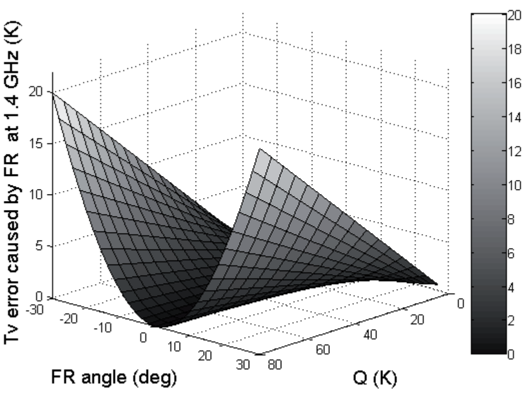

Fig. 1. Influence of Faraday rotation on T_v at 1.4 GHz. The grade of grayscale denotes the magnitude of T_v error.

At L-band, the brightness temperature sensitivity to salinity could approach $\Delta T/\Delta S$ = 1 K/practical salinity units (psu) [20], while the sensitivity to soil moisture is larger (usually 2-4 K/percent moisture) [15]. The ocean salinity accuracy is in average 1 psu for a single overpass while the accuracy requirement for soil moisture is 4 % in SMOS mission [21]. The aim of SSS observation is to achieve an accuracy of 0.1-0.2 psu monthly by averaging the longtime satellite data according to SMOS and Aquarius mission [18, 22]. It demonstrates that the brightness temperature accuracy requirement for SSS is much higher than that for SM. So in our study, we pay more attention to the correction of SSS. We set a high accuracy requirement of 0.2 K for final correction and a low requirement of 1 K for a single SSS observation. The SM accuracy requirement is relatively lower. It is usually bigger than 2 K.

For correction of U at 10.7 GHz, Fig. 2 illustrates the error of the third Stokes parameter U caused by Faraday rotation. Because the effect of U on ΔU is small in (8), U is set to fixed value of 0.2 K in the calculation. At 10.7 GHz, FR which usually lies in -0.1° ~0.1° in 50° incidence angle is more than 50 times smaller than that at 1.4 GHz. The magnitude of FR can reach greater than 0.2° when the sun is active. From Fig. 2, we see that even small FR can cause large U error. Assuming that U is 0.5 K and Q is 75 K, ΔU can be as large as 0.21 K which is even half of U when FR is 0.08°. It has been augured that the retrieval accuracy of WindSat SSWD is affected by $|\varphi|$ from 0.08° and the retrieval error increases quickly when $|\varphi|$ is greater than 0.15° [14]. So FR correction for U is essential before wind vector retrieval. Moreover, for WindSat, the requirement of polarization rotation angle knowledge error is 0.05° and the calibration accuracy for U is 0.25 K [19]. Thus, in our study for correction of U, the accuracy requirement of FR angle estimation is set to be less than 0.05° and the brightness temperature correction residual error is less than 0.25 K.

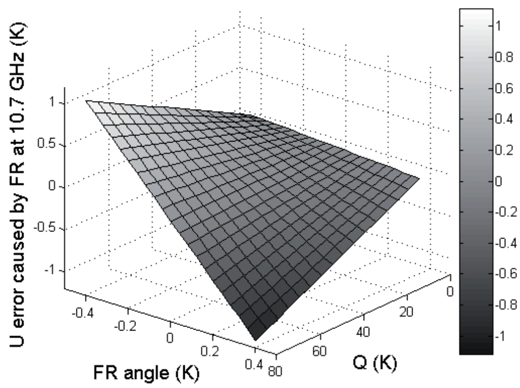

Fig. 2. Influence of Faraday rotation on U at 10.7 GHz. The grade of grayscale denotes the magnitude of U error.

4. Errors Correction

In most cases the brightness temperature errors caused by Faraday rotation need to be corrected. Generally, there are two approaches for FR correction of passive microwave remote sensing. One is to correct the errors by using auxiliary data according to (3) and (4). International Reference

Ionosphere (IRI) model and International Geomagnetic Reference Field (IGRF) model are usually used to provide VTEC and $\vec{B}$ data [14]. The other is to do the correction by applying the polarimetic mode of the radiometry. The cross polarization is employed and the estimation of FR is not necessary. Yueh illustrated a correction method by using the polarimetric radiometer with three polarization channels [11]. Ribó used the fully polarimetric mode of MIRAS for SMOS mission in FR correction [12]. In this section, we will compare the different methods for FR correction both at 1.4 GHz and at 10.7 GHz in detail. New methods and ideas of our own will be presented.

4.1 Data Preparation

For FR correction, the antenna temperatures are the input parameters. Because it is difficult to get the antenna temperatures data with no preprocessing, we simulate the four Stokes parameters brightness temperatures of the radiometer observation at 1.4 GHz and 10.7 GHz. The ionosphere data of an observation station located at (19.4° N, 109° E) in 2006 is obtained. Because the accuracy requirement for SSS is much higher than that for SM observation, we consider the situation in the sea. The simulation is done in the sea area nearby the observation station in Hainan province of China in 2006. The geophysical model is used to simulate the brightness temperatures from the earth [23], [24]. Then Faraday rotation is added to generate the antenna temperatures according to (6). The simulation is depicted in detail as Fig. 3. There are eight input parameters in the geophysical model. They are temperature, salinity, wind direction, wind speed of the sea surface, vertical columnar water vapor and cloud liquid water of the atmosphere, incidence angle and frequency. Vertical columnar water vapor is calculated by the radiosonde data. Sea surface Wind Field is taken from NCEP data. The other parameters are using random values within the physical value range in this area. Considering the influence of ionosphere, the real measured data of ionosphere electron density profiles of this observation station is applied to calculate FR as the standard value. Magnetic field is computed by IGRF model.

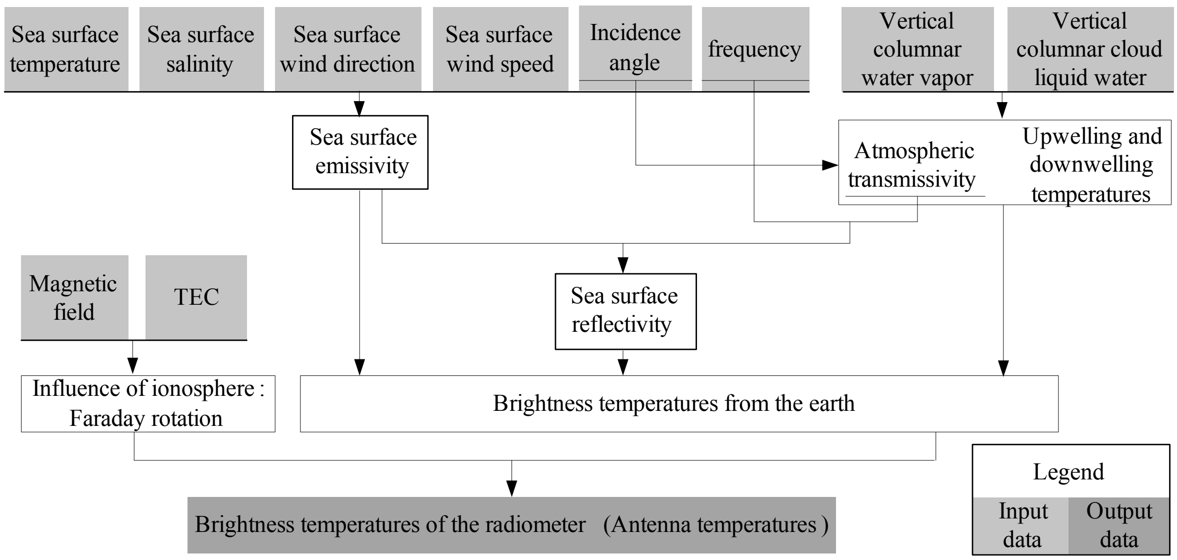

Fig. 3. The simulation flow of antenna temperatures.

We simulate the observation every day in 2006 and set the simulator parameters referring to SMOS, Aquarius and WindSat partially. The orbit is set to 800 km height with ascending mode and 98° inclination. At 1.4 GHz, the incidence angle is 38° corresponding to the central beam of Aquarius. The simulation is done with forward look of 0° azimuth angle for push broom mode. At 10.7 GHz, the incidence angle is 49.9° according to WindSat. The simulation is done with forward look of 0° azimuth angle and aft look of 180° azimuth angle for conical scanning.

4.2 1.4 GHz Correction for T_v

At 1.4 GHz, we are concerning about the correction of T_v. According to correction by auxiliary data, if the scan geometry, local time and satellite location are known, Faraday rotation can be computed based on (4). Then the error can be removed by inversing the process of (6). In application, total electron content (TEC) is the main error source of FR calculation. To get the real measured electron density profiles is difficult at the same time of observation. So IRI model is usually used to estimate the TEC. However, IRI model will underestimate (overestimate) the TEC when solar activity is high (low) [25]. Besides, for traditional radiometers with vertical and horizontal channels, only correction by auxiliary data is available because no cross polarization channels brightness temperatures (U and V) can be used for correction. In this condition, the formula of Faraday rotation on brightness temperatures is changed to (9) shown as follow. The correction is to do the inverse process.

$$\begin{pmatrix} T_{va} \\ T_{ha} \end{pmatrix} = \begin{pmatrix} \cos^2(\varphi) & \sin^2(\varphi) \\ \sin^2(\varphi) & \cos^2(\varphi) \end{pmatrix} \begin{pmatrix} T_v \\ T_h \end{pmatrix} \tag{9}$$

It is easy to prove that (9) is the simplified form of (6) when U is zero. It will introduce an additional residual error of $-0.5\tan(2\varphi)\cdot U$ in T_v correction. So for FR correction by auxiliary data, using IRI model to estimate TEC is a common method. The situation can be divided into two parts: one for correction with U for the polarimetric radiometer, the other for correction without U for the traditional two-channel radiometer.

Considering Faraday rotation correction by polarimetric mode, Yueh method is based on the assumption that the surfaces are azimuthally symmetric with no preferred direction of orientation. So the third Stokes parameter U is zero. Even actually there are nonazimuthally symmetric surfaces, U of the observation is very small (a few tenths of 1 K) at L-band and its contribution can be ignored in the following way:

$$\begin{aligned} Q_a &= Q\cos(\varphi) \\ U_a &= Q\sin(\varphi) \end{aligned} \tag{10}$$

The estimated Q after correction is:

$$Q_{estimate} = \sqrt{Q_a^2 + U_a^2}\,. \tag{11}$$

Thus the estimated T_v, T_h and φ after correction are:

$$\begin{aligned} T_{v\_estimate} &= T_{va} + 0.5(Q_{estimate} - Q_a) \\ T_{h\_estimate} &= T_{ha} + 0.5(Q_{estimate} - Q_a) \\ \varphi_{estimate} &= 0.5\arctan(U_a/Q_a) \end{aligned} \tag{12}$$

An in-depth error analysis is presented in literature [26], [27] which indicates that errors on polarization rotation (including Faraday rotation) can be effectively corrected by Yueh method.

In Ribó method, the polarimetric brightness temperature matrix $[T_{VH}]$ is used to demonstrate the effect of polarization rotation:

$$[T_{VH}] = \begin{bmatrix} T_{VV} & T_{VH} \\ T_{VH}^* & T_{HH} \end{bmatrix} \tag{13}$$

where $[T_{VH}]$ is a coherency matrix, and $T_{VV} = T_v$, $T_{HH} = T_h$, $T_{VH} = U/2 + iV/2$.

Similarly, the cross polarization of the earth scene is neglected under the assumption that the polarimetric brightness temperature matrix is diagonal ($T_{VH} = T_{HV} = 0$). Then the eigenvalues are used for correction. Because the eigenvalues of $[T_{VH}]$ remain the same before and after Faraday rotation, after correction they can be written as:

$$\lambda_{1,2} = \frac{\hat{T}_{VV} + \hat{T}_{HH}}{2} \pm \frac{\sqrt{\left(\hat{T}_{VV} - \hat{T}_{HH}\right)^2 + 4\left|\hat{T}_{VH}\right|^2}}{2} \tag{14}$$

$\hat{T}_{VV}$, $\hat{T}_{HH}$ and $\hat{T}_{VH}$ refer to the antenna temperatures which are equal to T_{va}, T_{ha} and $U_a/2 + iV_a/2$ respectively. The estimated T_v, T_h, Q and φ after correction are:

$$\begin{aligned} T_{v\_estimate} &= \lambda_1, \\ T_{h\_estimate} &= \lambda_2, \\ Q_{estimate} &= \sqrt{Q_a^2 + U_a^2 + V_a^2}, \\ \varphi_{estimate} &= 0.5\arctan(U_a/Q_a). \end{aligned} \tag{15}$$

We compare the correction effects of Yueh and Ribó methods. For Faraday rotation correction by polarimetric mode, only the antenna temperatures are the input parameters. The estimation of FR is not necessary. Besides, FR angles estimated by Yueh and Ribó methods are equal. We can prove that in ideal cases with no noise, Ribó method is equivalent to the Yueh method when $V_a = 0$. The correction accuracy has no relation to FR in this condition. Ribó method always has a little more residual correction error than Yueh because of the influence of V. Fig. 4 (a) shows the correction accuracy by Yueh method. Fig. 4 (b) describes the excessive correction residual error of Ribó method compared with Yueh. The excessive error of Ribó is mainly determined by V and Q. Under most circumstances, the polarimetic mode method has correction accuracy better than 0.05 K. The performance of Yueh method is a little better than that of Ribó.

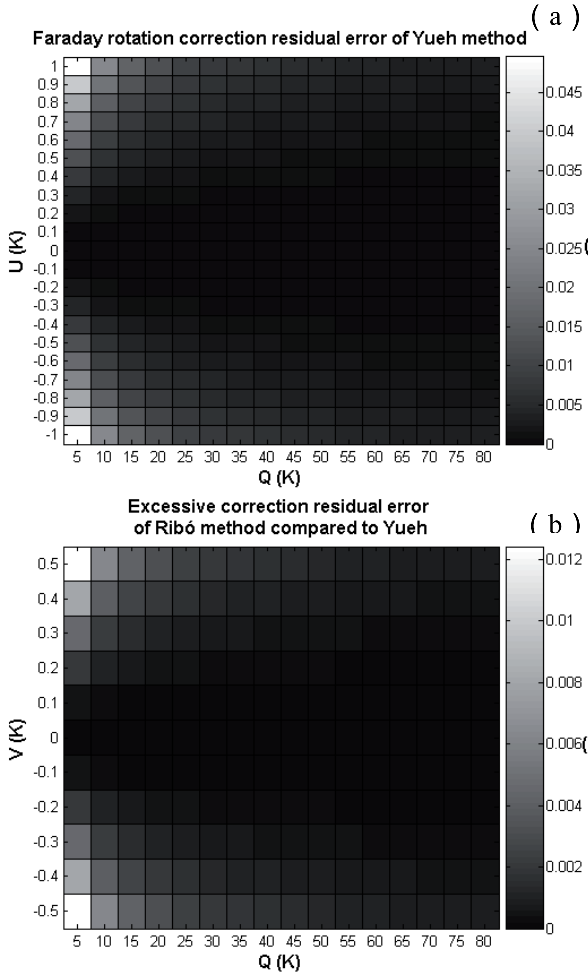

Fig. 4. Faraday rotation correction by methods of Yueh and Ribó in ideal cases with no noise. (a) Faraday rotation correction residual error of Yueh method; (b) Excessive correction residual error of Ribó method compared to Yueh.

In order to evaluate the performances of the two approaches for FR correction at 1.4 GHz, we use the simulated brightness temperatures described in section 4.1. For the first run, the simulation is done at 6:00 LT every day in 2006.

We use root mean square error (RMSE) to measure the brightness temperatures correction accuracy of different methods. As shown in Tab. 2, Yueh method is best while IRI model correction without U performs worst. The correction error of IRI model is almost twice larger than that of polarimetric mode in magnitude. The difference between Yuen and Ribó methods is small because Ribó introduces V in correction which introduces the additional error. It is clear that all four methods meet the accuracy requirement for SSS observation. The brightness temperature residual errors are small. The reason is that 2006 meets the bottom in a 11 years solar cycle and sun is not active especially at 6:00 LT. The average FR at 6:00 LT a year is -1.0535°. When the solar activity reaches the maximum (in 1989 and 1999), the peak values of VTEC and FR which are increased by a factor of 2 are expected [25]. So in 2006, small FR causes small FR estimate errors (0.8686° for IRI model and 0.1733° for Yueh and Ribó method) and leads to small residual errors of brightness temperature according to Tab. 2 and Fig. 1.

If we run the computation at 18:00 LT when the sun activity reaches the peak in a day, (average FR is -4.6670° a year) the residual errors will be larger especially for IRI model correction. In this case, residual error of IRI model correction without U (0.3067 K) is out of the 0.2 K accuracy requirement of SSS final correction we set before. Besides, FR estimate errors also become larger at 18:00 LT and brightness temperature errors of IRI model correction is much greater than polarimetric mode correction. It is known that the residual brightness temperature correction errors and FR estimate errors of IRI model are associated with the TEC estimation accuracy. The corresponding errors of polarimetric mode are only related to the input antenna temperatures. Thus we can expect greater errors in sunspot active year for IRI model correction. However, the accuracy for Yueh and Ribó methods will not vary severely in different ionosphere conditions. In addition, in large incidence angle (such as 50°), residual brightness temperature correction errors will become larger with the increase of FR angle φ and the second Stokes parameter Q.

	IRI model correction (without U)	IRI model correction (with U)	Yueh method	Ribó method
Residual brightness temperature correction errors (6:00) (K)	0.0296	0.0106	4.2271×10^{-4}	4.8401×10^{-4}
FR estimate errors (6:00) (deg)	0.8686	0.8686	0.1733	0.1733
Residual brightness temperature correction errors (18:00) (K)	0.3067	0.1021	4.2672×10^{-4}	4.9033×10^{-4}
FR estimate errors (18:00) (deg)	2.6591	2.6591	0.1747	0.1747

Tab. 2. Estimation of Faraday rotation and correction of T_V with different methods.

All simulations above are in ideal cases, there is no consideration on the hardware configuration and the noise. Although several researches have been done on Faraday rotation correction combining with the hardware configuration about Aquarius and SMOS mission [28-31], we are not concerned about this issue because the hardware systems of different radiometers (such as SMOS and Aquarius) are different and are hard to compare. Only the correction algorithm is what we concern about. However, the noise should be considered since it is inevitable in all receiving system of radiometers. Noise directly influences the correction effect. We use Monte Carlo mode to simulate the knowledge errors of received brightness temperatures which is considered as noise. Because the orthogonal channel brightness temperature T_v is to be corrected, we firstly add errors of Gaussian distribution with known σ and zero mean to the correlative channel brightness temperatures (U and V) to see the influence of cross polarization on FR correction.

The simulation is run at 18:00 LT and the results are shown in Tab. 3. IRI model correction with U is included in the comparison. For correction of brightness temperatures, all the methods are sensitive to noise especially for correction by polarimetric mode and the residual errors become larger when σ increases from 0.1 to 0.5. Yueh method performs best while the differences between Yueh and Ribó methods are very small, IRI model correction performs worst. The residual error of IRI model is close to the high accuracy requirement (0.2 K) of SSS observation. It should be noted that in high solar activity year (1999), FR may be twice as large as the value in 2006. Considering the extreme cases, for example, in low-mid latitudes regions, at high incidence angle (50°), with high solar activity (SSN > 100) and the worst scan geometry, FR bigger than 20° as well as the IRI model with an uncertainty of about 1/3, the residual correction error can be greater than 1 K. This error exceeds the requirement for a single observation of SSS. It will influence SSS retrieval significantly. Fortunately, the residual errors of the correction by polarimetric mode are less than 0.05 K in our simulation. They can be expected to be less than 0.2 K in all various environmental conditions because the accuracy has no relation to ionosphere TEC. For FR estimation, FR estimate error by IRI model method is not affected by U. The error of 2.6591° is large and does not change with σ.

Yueh and Ribó methods have the same FR estimation process which has the accuracy of less than 0.5°. In addition, if we know FR angle φ, the ionosphere VTEC can be retrieved by inversing (4). According to [11], Yueh method can potentially provide VTEC measurement with an accuracy of 1 TECU.

Noise (K)	Residual brightness temperature correction errors (K)			Faraday rotation estimate errors (deg)	
	IRI model correction (with U)	Yueh method	Ribó method	IRI model correction (with U)	Yueh and Ribó methods
σ=0.1	0.1032	0.0093	0.0094	2.6591	0.1955
σ=0.2	0.1056	0.0174	0.0175	2.6591	0.2488
σ=0.3	0.1069	0.0281	0.0282	2.6591	0.2998
σ=0.4	0.1147	0.0392	0.0393	2.6591	0.3915
σ=0.5	0.1169	0.0477	0.0480	2.6591	0.4431

Tab. 3. Estimation of Faraday rotation and correction of T_v with noise on U and V.

Actually, noise not only exits in correlative channels but also in orthogonal channels. We then add noise to the orthogonal channels brightness temperatures (T_v and T_h) as shown in Tab. 4. Yueh and Ribó methods have almost the same performance because V is relatively small. Noise here introduces greater errors. Even correction by polarimetric mode will render a residual error larger than 0.2 K when σ is above 0.2. This means that the corresponding error exceeds the high accuracy requirement for SSS observation for final correction. When σ becomes larger, the effect of correction algorithm has almost been covered by noise. Although polarimetric mode correction is better, differences between residual errors of diverse methods become unobvious. For example, when σ is 0.5 K, the brightness temperature error to be corrected is 0.6343 K, the residual errors of four correction methods are all close to 0.5 K in this case. There are little differences in the results. In reality, the calibration accuracy of orthogonal channels can hardly reach 0.5 K. Thus FR correction residual errors are not the main error sources for radiometer observation in T_v and T_h especially when FR is not large. The accuracy of 0.2 psu for SSS observation is not the target for the single overpass of measurement. It can be reached by using the technology of averaging the observational data in time and space. Even residual error of correction by polarimetric mode exceeds 0.2 K, the accuracy requirement of SSS can be reached by using this technology. However, because correction by IRI model causes residual error greater than 1 K in extreme cases, the accuracy of 0.2 psu can hardly be guaranteed by averaging the observational data. Considering observation of SM, the sensitivity and the dynamic range are much larger. Even more than 1 K residual error of correction by IRI model is within its accuracy requirement [10]. Thus, all four methods of the two known approaches are applicable to FR correction of SM.

Noise (K)	Brightness temperature errors to be corrected (K)	Residual brightness temperature correction errors (K)			
		IRI model correction (without U)	IRI model correction (with U)	Yueh method	Ribó method
σ=0.1	0.4321	0.3311	0.1368	0.1035	0.1035
σ=0.2	0.4591	0.3734	0.2190	0.1990	0.1990
σ=0.3	0.5068	0.4227	0.3038	0.2881	0.2881
σ=0.4	0.6077	0.5184	0.4190	0.4051	0.4051
σ=0.5	0.6343	0.6092	0.5012	0.4974	0.4974

Tab. 4. Faraday rotation correction of T_v with noise on orthogonal channel brightness temperatures (T_v and T_h).

According to the analysis above, Faraday rotation correction by polarimetric mode is better than IRI model in the condition both excluding and including the noise. Yueh method performs best while IRI model correction (without U) is worst. For the situation in a single incidence angle, all the methods can be used for correction in SM observation while correction by IRI model can not meet the accuracy requirement for SSS measurement in some extreme cases. Noise in the orthogonal channels can introduce much larger errors in FR correction than correlative channels. In practical situation, it is hard to meet the 0.1 ~0.2 psu requirement of SSS observation for a single overpass of measurement. The approach of data averaging is an effective way to solve this problem. Besides, for FR correction of the traditional two-channel radiometer, only correction by IRI model without parameter U is available. Thus traditional radiometer can not achieve high observational accuracy because of the large residual correction error.

4.3 10.7 GHz Correction for *U*

At 10.7 GHz, we are concerning about correction of U. The approaches of correction by polarimetric mode and by auxiliary data are considered again. According to correction by polarimetric mode, Yueh and Ribó methods both base on the prerequisite that there is no cross polarization between T_v and T_h. This means that the third and fourth Stokes parameters (*U* and *V*) are zero. However, sea surface wind direction retrieval has a close relation to *U*. If *U* is zero, no wind direction information can be used. Moreover, Faraday rotation estimated by polarimetric mode is far away from the true value in this case. For example, if $Q = 75$ K, $U = 0.5$ K and FR true value equals to -0.1°, FR estimated by polarimetric mode will be 0.09°. The error is 0.19° which is much greater than the 0.05° polarization rotation accuracy requirement for WindSat. Therefore, correction by polarimetric mode is not feasible for *U* correction at 10.7 GHz.

Considering correction by auxiliary data, IRI model is what we first think of. Actually it has been already used in Faraday rotation correction for WindSat [14]. According to WindSat observation, almost 90 % FR angles lie in the range of -0.1° to 0.1°. In this case, there is not any serious problem to use IRI model for correction. However, FR can reach greater than 0.2° especially 0.6° in extreme cases. The uncertainty of TEC estimated by IRI model can reach up to 1/3 FR [25]. This means that the corresponding FR estimate error is beyond 0.05° which is unacceptable for WindSat.

In order to improve the correction accuracy, we propose a new method of correcting Faraday rotation by using TEC data released by international GNSS service (IGS) instead of IRI model. IGS distributes global GNSS observation TEC products (rapid solution and final solution) every two hours a day. The latency of its rapid ionospheric TEC grid data which we used is within 24 hours [32]. Here we interpolate the TEC data to the objective point in Hainan province which is the same location as described in section 4.1. By comparing FR angle calculated by the real measured TEC with the corresponding values of the two methods mentioned above for a whole year in 2006, we get a much better result for correction by IGS data than IRI model as described in Tab. 5. The errors are expressed by RMSE. All the calculations are run at 18:00 LT when the sun activity reaches the peak in a day. Forward look of 0° azimuth angle and aft look of 180° azimuth angle have been considered.

	Mean absolute value of FR angle (deg)	FR estimate error of IRI model correction (deg)	FR estimate error of IGS data correction (deg)
Forward look	0.1059	0.0591	0.0348
Aft look	0.0394	0.0220	0.0129

Tab. 5. Comparison of Faraday rotation estimate errors.

From Tab. 5, it is clear that the FR estimate error of correction by IGS data is much less than that of IRI model. According to (4), scan geometry is an important factor to determine FR angle. Fig. 5 shows the variation of FR at the area of the observation station for the conical scanning geometry. Faraday rotation is larger for forward look than aft look. It has been studied that FR usually meets the largest negative (positive) value with forward (aft) looking mode at low northern latitudes during the ascending swaths [33]. As mentioned above, WindSat polarization rotation accuracy is 0.05°. For aft look, FR estimate errors of the two methods are all under 0.05°. However, only IGS data method can meet the accuracy for forward look.

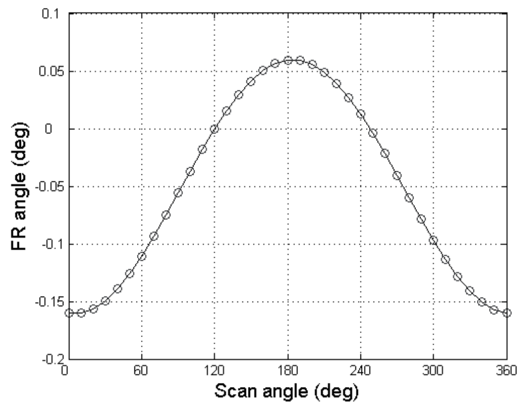

Fig. 5. Faraday rotation for conical scanning geometry. FR is calculated by IRI model with sun spot number (SSN) of 28.

Here an in-depth analysis is presented. We run the simulation again to study the influence of Faraday rotation correction on the third Stokes parameter *U*. The simulation data described in section 4.1 is used. The results are shown in Fig. 6. It should be noted that IGS data used in our study is absent from the 356th to 365th day in 2006. It is clear that FR correction by IGS data matches the standard value well according to Fig. 6 (a) and (c). The correction quantity of IRI model is generally higher than the standard value. Fig. 6 (b) and (d) gives the distribution of the residual error of *U* in 2006 by two methods. The RMS value of the residual error of IGS data correction for forward look is 0.0789 K which is much less than the residual error of 0.1350 K from IRI model. For aft look, the influence of FR becomes smaller. IGS data correction also performs better. The residual error is 0.0294 K which is less than the 0.0502 K error of IRI model. We can attribute the difference on correction results to that TEC of IGS data which is retrieved from global GNSS observation has a higher accuracy than that of IRI model which is the value of statistical average. The WindSat calibration accuracy requirement is 0.25 K for the third Stokes parameter *U* [19]. So in low solar activity year such as 2006, both methods meet the accuracy and IGS correction performs better.

To accurately get the third Stokes parameter *U* is hard according to the calibration technology in practical cases, so we consider Faraday rotation correction with noise again. Noise with zero mean and known σ is added into *U* by Monte Carlo mode. Comparison of the two correction methods are run again to see which is better as shown in Tab. 6. Because the influence of FR for the forward look is larger, we consider this situation. It is observed that even with 0.2 K noise, correction by IGS data can meet the accuracy requirement of 0.25 K for WindSat. We also find that the differences between two correction methods become smaller when the noise is getting large. The excellent performance of IGS data correction may be covered by noise. Then noise is added into the orthogonal channel brightness temperatures (T_v and T_h). However, as the magnitude of FR at 10.7 GHz is small, the sine term in (6) is near zero, U isn't sensitive to the error of Q. Even if 0.5 K noise is added, the change of residual error of U for two methods is less than 0.005 K. Besides, what we should pay attention to is that correction by IGS data is only feasible for near real time correction. This is because IGS product is not the real time observation data but released in several hours delay. So for real time correction, only IRI model can be chosen and for near real time correction or final data correction of radiometer data, IGS data method is much better.

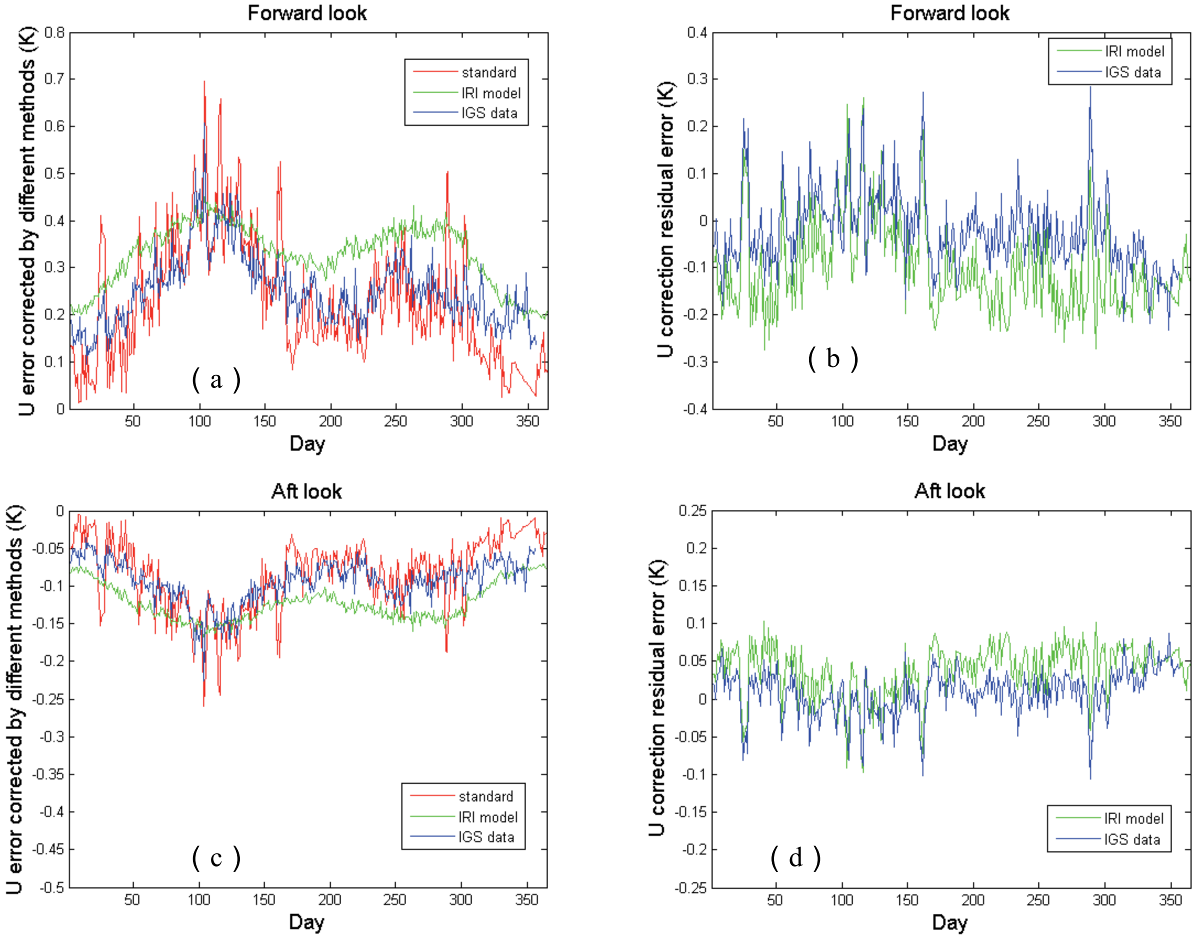

Fig. 6. Comparison of Faraday rotation corrections for U by IRI model and IGS data at 10.7 GHz in 2006. The red line, green line and blue line indicate the standard value, results of IRI model and IGS data respectively. (a), (c) U error corrected by different methods for forward and aft look; (b), (d) Residual errors of U corrected by different methods for forward and aft look.

Noise (K)	Brightness temperature errors to be corrected (K)	Residual error of IRI model correction (K)	Residual error of IGS data correction (K)
σ=0	0.2768	0.1350	0.0789
σ=0.05	0.2835	0.1428	0.0935
σ=0.1	0.2953	0.1636	0.1246
σ=0.15	0.3241	0.2174	0.1801
σ=0.2	0.3372	0.2585	0.2269
σ=0.25	0.3739	0.2880	0.2658

Tab. 6. Correction of the third Stokes parameter brightness temperature U with noise in different magnitude.

The correction result of IGS data is superior to IRI model because it provides more accurate VTEC than the latter. The TEC released by IGS has an accuracy about 2-9 TECU. However, as mentioned above, Yueh method can potentially provide the estimation of TEC with 1 TECU at 1.4 GHz even though it is invalid at 10.7 GHz. For correction by auxiliary data, the more accurate TEC data is used, the less residual error of FR correction we can get. So for future application, we can propose an idea of combining observation of SSS at 1.4 GHz and sea surface wind vector at 10.7 GHz together. If the two radiometers can fly in satellite formation, such as "A-Train" satellite formation of NASA, the FR correction will be easier. At 1.4 GHz, correction by polarimetric mode is feasible while the estimated VTEC can be used for FR correction at 10.7 GHz. Theoretically using TEC provided by polarimetric mode at 1.4 GHz can double the FR correction accuracy based on IGS data at 10.7 GHz. Based upon this assumption, the observation at the two frequencies should have almost the same scan field on the earth surface. Besides, the time interval between two observations should be short and TEC can be considered with no variation. Because the spatial resolution at 1.4 GHz is less than that at 10.7 GHz, TEC at 1.4 GHz should be interpolated to the incident point position of thin layer at 10.7 GHz. More consideration of geolocation and scan geometry should be considered in future when matching the TEC data.

5. Conclusions

In this paper, Faraday rotation correction for passive microwave remote sensing from space is discussed. We focus on FR correction especially for T_v at 1.4 GHz and for U at 10.7 GHz. Comparison between two approaches (correction by auxiliary data and by polarimetric mode) has been run. Besides, for correction by auxiliary data, we propose a new method of correcting FR by using IGS TEC data.

At 1.4 GHz, correction by polarimetric mode performs better than correction by auxiliary data. Yueh method performs best even in the condition with noise. Under the observation in a single incidence angle, all methods are available for SM measurement while correction by IRI model may become invalid in some cases for SSS observation. The advantage of correction by auxiliary data is that it can be applied in the traditional two-channel radiometer. In this case, only the orthogonal channels are used for correction while the correlative channels are not included. The disadvantage of correction by polarization mode is that cross polarization channels should be employed during the design phase of radiometer system. The additional price to pay is the complexity of polarimetric operation of the radiometer. At 10.7 GHz, correction by polarization mode fails, only correction by auxiliary data is feasible. Compared with correction by IRI model, a new method of using IGS TEC data for FR correction is proposed. Simulation results show that it greatly increases the correction accuracy and can be used for near real time or final data correction instead of IRI model.

In this study, we presented a comprehensive analysis of Faraday rotation for passive microwave remote sensing from space. In future work, the combination between simulation of hardware system and retrieval of geophysical parameters should be done to study the influence of FR on radiometer observation in practical situations.

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